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Experimental plan and design of two experiments for graphite irradiation at temperatures up to 1500 °C in the target region of the high flux isotope reactor

J.L. McDuffee *, T.D. Burchell, D.W. Heatherly, K.R. Thoms

Oak Ridge National Laboratory, UT-Battelle, Inc., P.O. Box 2008, Oak Ridge, TN 37831, USA

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ABSTRACT

Two irradiation capsules have been designed for the target region of the high flux isotope reactor (HFIR). The objective is to provide dimensional change and physical property data for four candidate next generation nuclear plant (NGNP) graphites. The capsules will reach peak doses of ∼1.59 and ∼4.76 dpa, respectively, at temperatures of 900, 1200, and 1500 °C.

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1. Introduction

HTV-1 and -2 are high flux isotope reactor (HFIR) high-temperature irradiation capsules designed to provide dimensional change and physical property data for the NGNP program, and to support the design of ATR high-temperature creep experiments (AGC series of capsules) [1]. The HTV-1 and -2 capsules will reach peak doses of ∼1.59 and ∼4.76 displacements per atom (dpa), respectively, and each capsule contains temperature zones designed to operate at either 900, 1200, or 1500 °C. This paper describes the experiment design that will be used to irradiate the specimens in the HFIR target region. The data to be obtained from these irradiation capsules include:

- Irradiation induced dimensional changes.
- Irradiation induced density changes.
- The effect of irradiation on the room temperature thermal conductivity.
- The effect of irradiation on the elastic constants, E, G, and υ.
- The effect of irradiation on the compressive (brittle ring) strength.

2. Specimens

The graphite grades to be included in the HTV capsules are: SGL grade NBG-18, which is the candidate-grade for pebble bed modular reactor (PBMR) core structures; NBG-17, which is a finer-grained version of NBG-18 and is a candidate for the prismatic block reactor fuel elements and core structures; GrafTech grade PCEA which is a candidate for the prismatic block reactor fuel elements and core structures; Toyo Tanso grade IG-430 which is Japan Atomic Energy Research Institute's (JAERI) preference for their Gas Turbine High Temperature Reactor (GTHTR) 300 concept; SGL grade H-451 will be included as a reference grade to link with historical data.

The graphite specimens for the HTV-1 and -2 capsules are solid cylinders with a nominal 5.3-mm thickness and an outer diameter of 10.2 mm, 8.9 mm, or 7.6 mm, depending on the target specimen temperature and location. There are a total of eight subcapsules in each capsule, and eight specimens in each subcapsule, for a total of 64 specimens per capsule and 128 total specimens. Each subcapsule will have a design temperature of 900 °C, 1200 °C, or 1500 °C. Table 1 summarizes the graphite specimens to be used in the experiments.

Capsule HTV-1 is a one-cycle experiment, while HTV-2 will remain in the HFIR core for three cycles. The HFIR flux spectrum is symmetrical about the reactor mid-plane, and thus, by careful arrangement of the samples, a useful range of doses may be attained for each graphite grade. A detailed fluence layout is shown in Fig. 1.

3. Capsule design

The HTV capsules are divided into eight subcapsules, each with eight specimens. A typical subcapsule is shown in Fig. 2. The innermost region is a stack of eight specimens and one graphite melt-material container, which is fabricated to the same shape and size as a specimen. The specimens in the stack will all have the same outer diameter of 10.2 mm, 8.9 mm, or 0.8 mm, depending on the temperature and location of the subcapsule.

The melt-material container, shown in Fig. 3, is always at the axial center position of the specimen stack. The container is designed such that post-irradiation disassembly and inspection can be accomplished easily by holding the outer container and

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* Corresponding author.
E-mail address: mcduffeej@ornl.gov (J.L. McDuffee).

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Table 1
HTV graphite specimens

Graphite	Reactor vendor	Proposed use	Source	Process details	Remarks
H-451	General atomics	Prismatic fuel element and replaceable reflector	SGL carbon (USA)	Petroleum coke, extruded, medium grain	Historical reference only a few samples
PCEA	AREVA	Prismatic fuel and replaceable block	GrafTech International (USA)	Petroleum coke, extruded, medium grain	AREVA wants to construct the entire graphite core out of the same graphite
NGB-17	PBMR AREVA	Pebble bed reflector structure and insulation blocks; Prismatic Fuel element and replaceable reflector	SGL carbon (Germany/ France)	Pitch coke, vibrationally molded, medium grain	NGB-17 is a candidate for PBMR replaceable reflector and core structures. AREVA wants to construct the entire graphite core out of the same graphite. NBG-17 is finer grain than NBG-18
NGB-18	JAERI	Prismatic fuel element, replaceable reflector, and core support pedestals	Toyo Tanso (Japan)	Pitch coke, isostatically molded, fine grain	JAERI wants to use this graphite in the GTHTR 300

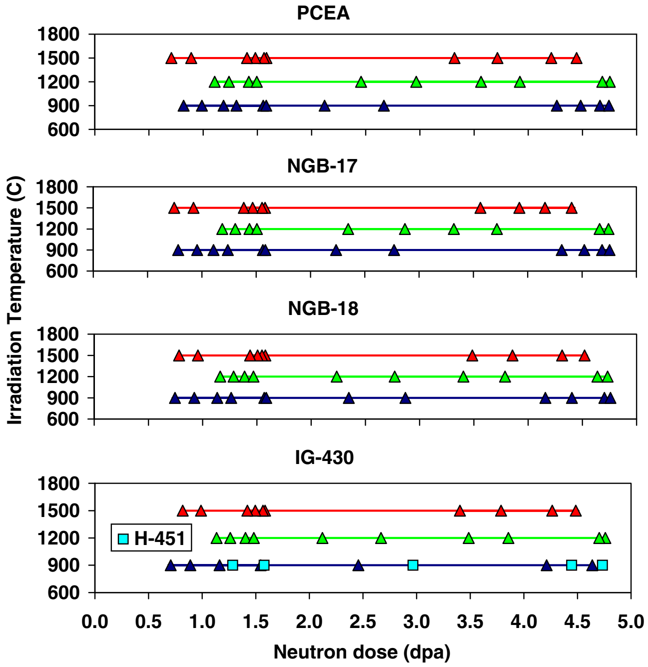

Fig. 1. Dose and design temperature arrangement for HTV-1 and -2 capsules.

pushing through the small center hole at the top of the outer container.

As shown in Fig. 2, the specimen stack is surrounded by a 0.5-mm thick POCO graphite sleeve, which prevents contact between the specimens and the third layer – the niobium holder. Sandwiched between the niobium holder and the outer aluminum housing is a thin layer of neon gas.

The temperature in the subcapsule is controlled by the thickness of the neon gas layer between the niobium holder and the capsule outer aluminum housing. The holder has different outer diameters at the top, middle, and bottom to compensate for heat losses through the subcapsule ends and for the heating profile, which peaks at the horizontal mid-plane (HMP) of the reactor and falls off toward the top and bottom.

A centering thimble, shown in Fig. 4, is inserted into the top and bottom of each holder. This part holds the specimens in position inside the holder and centers the subcapsule inside the housing. The prongs of the thimble are designed to hold the subcapsule in place while minimizing the heat losses through the subcapsule ends. Small wires are inserted through matching holes in the holder and thimble to ensure the thimbles stay in place during assembly and irradiation.

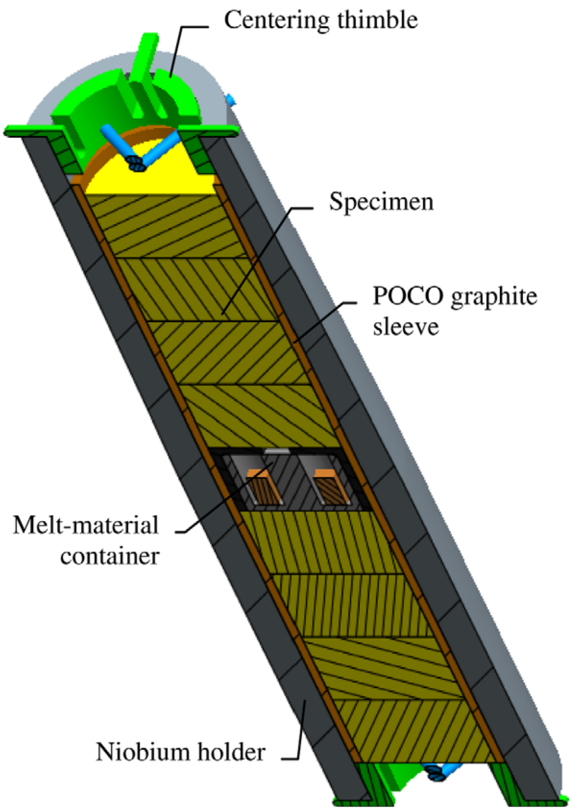

Fig. 2. Subcapsule assembly.

The subcapsules are separated with stacked sheets of thin grafoil wafers splined on a thin-walled molybdenum tube, as shown in Fig. 5. Each end of a stack is fitted with a shoulder that is sized to insert inside the inner diameter of a centering thimble. Dosimetry parts are inserted into the grafoil assembly. Fig. 6 shows a view of the top subcapsule with the grafoil spacer inserts.

4. Thermal analysis

The thermal analysis and design of the HTV capsules is accomplished in two steps: (1) determination of appropriate heat generation rates and (2) a coupled thermal/structural analysis that includes the conduction, convection, and radiation solution and the thermal expansion of the capsule parts. MCNP Version 5 [2] is the primary tool used to estimate heat generation rates. The ANSYS [3] finite element software is used to solve the coupled thermal/structural solution.

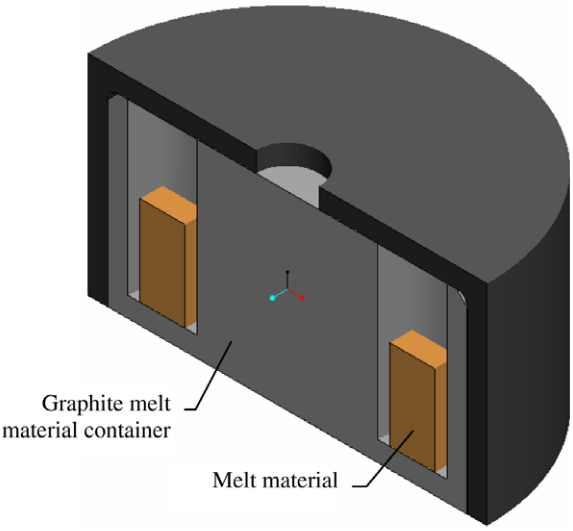

Fig. 3. Melt-material container.

Fig. 4. Centering thimble design.

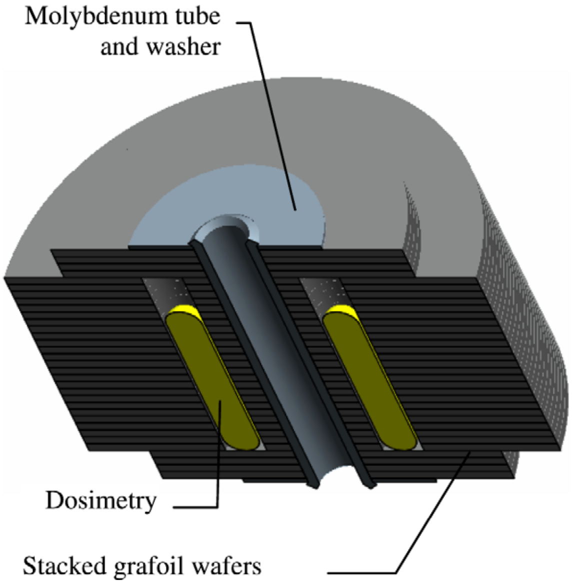

Fig. 5. Grafoil separator design.

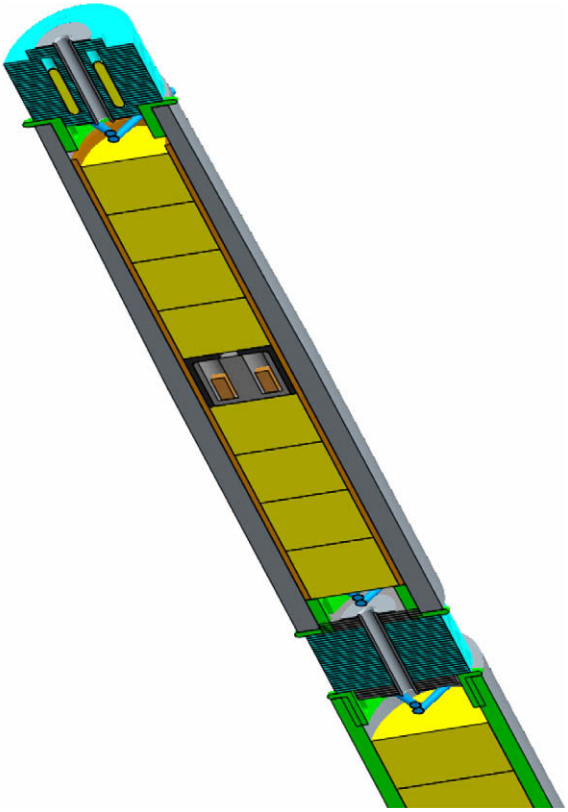

Fig. 6. Subcapsule 1 design with grafoil spacers.

4.1. Heat generation rates

The MCNP model used to estimate the heat generation rates of the HTV materials is shown in Fig. 7. The loading configuration is based on the actual HFIR loading for Cycle 400. The outer aluminum shroud is simplified into a simple cylinder with the same coolant flow area and cross-sectional area. This will preserve the

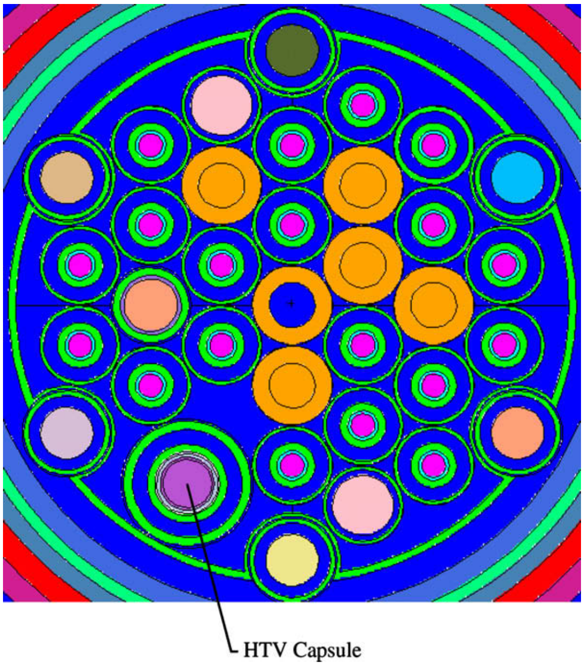

Fig. 7. Target region of HFIR Showing the HTV capsule in positions B1-C1-C2.

Table 2
Material heat generation rates for BOC, EOC, and design

Material	Decay	BOC			EOC			Total design
		Prompt fission	Fission product decay	Total	Prompt fission	Fission product decay	Total	
Graphite	–	21.8	12.6	34.4	20.6	10.7	31.3	32.8
Niobium	–	32.6	26.4	59.0	30.0	24.0	54.0	56.5
Molybdenum	0.3	33.5	27.2	61.0	28.8	27.9	57.0	59.0
Vanadium	19.4	22.2	11.4	53.0			[a]	53.0
Al 6061	1.5	20.1	13.4	35.0	18.1	11.9	31.5	33.0

[a] Vanadium was not included in the EOC calculation because it represents such a small amount of material and does not significantly affect the temperature of surrounding components.

water and aluminum volume in the capsule, which is important for accurately estimating neutron moderating affects. The model was developed with both beginning-of-cycle (BOC) and end-of-cycle (EOC) fuel loading/control plate configuration options.

The MCNP model was run in (n,p) mode using a fission source (kcode) to obtain the neutron energy absorption rate (e.g., due to neutron scattering and [n,γ] reactions) and the direct photon absorption rate from direct fission photons. A second calculation was developed to obtain the energy absorption due to photons originating from fission product decay. In this calculation, photons are assumed to originate in the core with the same radial and axial distribution as fissions in the original kcode calculation. The energy distribution of the fission product photons and the number of photons per fission was estimated using ORIGEN-S [4]. The activation and decay of capsule components also generates heat in some of the capsule materials. This effect was estimated using the FISPACT software [5]. Table 2 summarizes the peak heat generation rates for BOC, EOC, and design.

4.2. Finite element thermal analysis

The HTV-1 and -2 capsules are modeled in the ANSYS finite element program with an axisymmetric model that spans the full length of the reactor active region. There are three parts within the capsules that have non-axisymmetric features: (1) the melt-material 'specimens', (2) the dosimetry inserts in the grafoil separators, and (3) the centering thimbles. Both the melt-materials and the dosimetry inserts are very small parts that do not significantly affect the surrounding temperature profile. These items are modeled very approximately as vanadium-filled holes. In contrast, the centering thimbles are key components that control the amount of heat loss through the ends of each subcapsule. An axisymmetric

Drawing of an actual centering thimble

Axisymmetric model of a centering thimble

Fig. 8. Comparison of an actual centering thimble with the axisymmetric model.

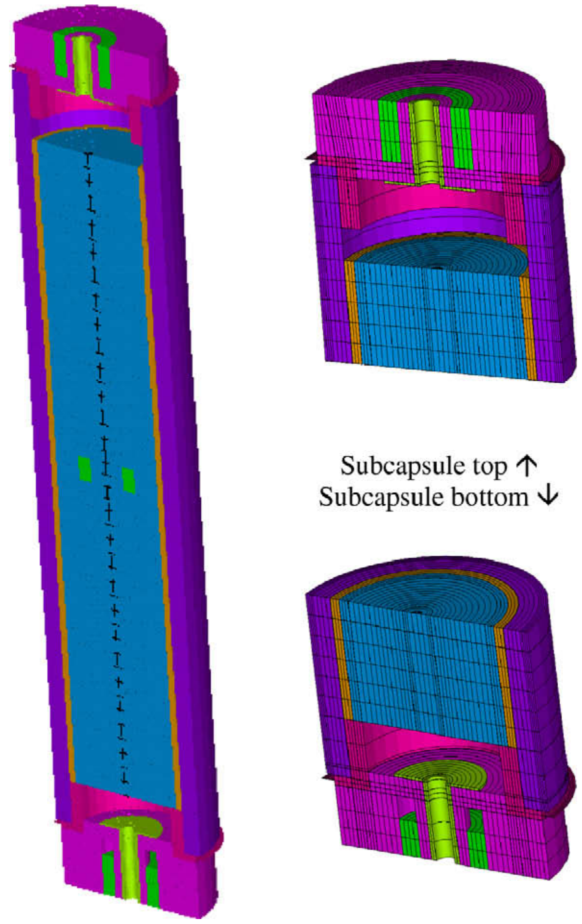

Fig. 9. Subcapsule ANSYS model.

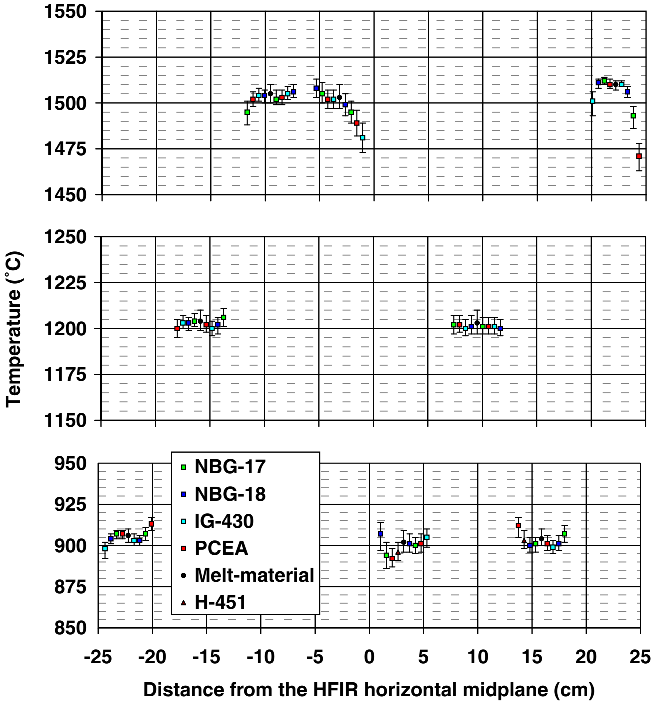

Fig. 10. Estimated specimen temperatures for HTV-1.

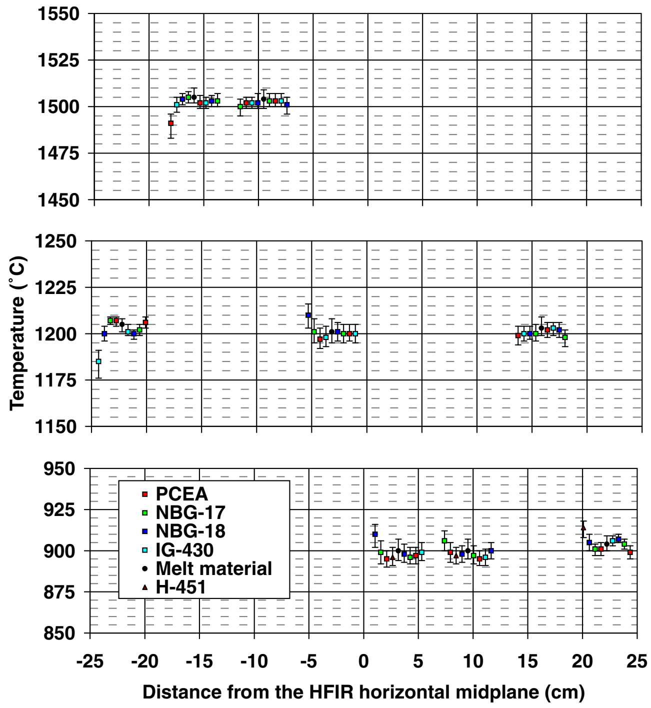

Fig. 11. Estimated specimen temperatures for HTV-2.

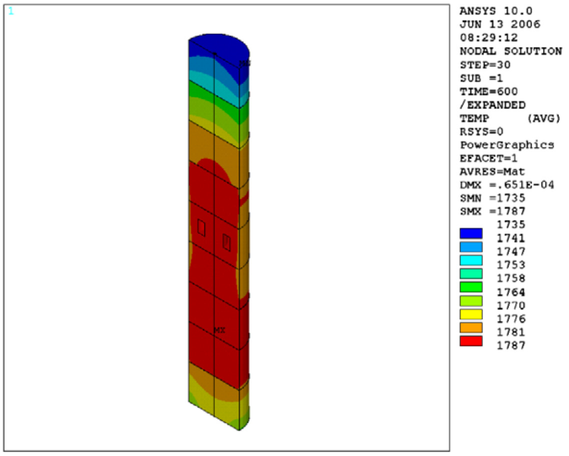

Fig. 12. Temperature profile for subcapsule 1 in HTV-1. This subcapsule has the largest temperature variation of all subcapsules. Temperature is in K.

approximation was developed by maintaining the total contact surface area, as shown in Fig. 8.

All the remaining parts are fundamentally axisymmetric, and no significant geometrical changes are required for the model. However, some features of the end parts at the top and bottom of the capsules are neglected because they are not relevant to the temperature profile inside the subcapsules. Fig. 9 shows the total axisymmetric model of a representative subcapsule. Note that all solid parts are separated by a 0.0127 mm (0.5 mil) neon gas layer to simulate the effects of thermal contact resistance.

The temperature goal for each subcapsule is achieved by selecting outer holder diameters at the top, middle, and bottom of each subcapsule. The final estimated specimen temperatures for HTV-1 and HTV-2 are shown in Figs. 10 and 11, respectively. The specimen types are shown by color. The minimum and maximum specimen temperatures are shown as error bars. (Note that the error bars do not represent uncertainty, but rather the as-modeled temperature range for each specimen.) Fig. 12 shows the temperature contour for subcapsule 1 of HTV-1, which has the largest specimen temperature variation of all subcapsules.

5. Conclusion

This paper describes the design of the HTV-1 and -2 HFIR high-temperature irradiation capsules. These capsules are designed to provide dimensional change and physical property data for the NGNP program, and to support the design of ATR high-temperature creep experiments (AGC series of capsules). Peak doses of ~1.59 and ~4.76 displacements per atom (dpa) will be attained for HTV-1 and -2, respectively, and each capsule contains temperature zones designed to operate at either 900, 1200, or 1500 °C.

Acknowledgements

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